	L #	Hits	Search Text	DBs
1	L1	1	6280813.pn.	USPAT
2	L2	653	hcp	USPAT
3	L3	0	1 and 2	USPAT
4	L4	96	coptcrb or cocrptb or co-pt-cr-b or co-cr-pt-b	USPAT
5	L5	0	2 near10 4	USPAT
6	L6	25	2 and 4	USPAT
7	L7	3	2 same 4	USPAT
8	L8	1	6268036.pn.	USPAT
9	L9	6673	exchange near4 coupl$3	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM TDB
10	L10	445010	ru or ruthenium	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM TDB
11	L11	2058	lattice near10 mismatch	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM TDB

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12	L12	2	9 and 10 and 11	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM TDB
13	L13	497507	exchange	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM TDB
14	L14	7	10 and 11 and 13	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM TDB
15	L15	5	14 not 12	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM TDB

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1	L1	445375	ru or ruthenium or ruco or rucr or ru-co or ru-cr or crru or coru or cr-ru or co-ru	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM TDB
2	L2	98924	nonmagnetic or non-magnetic	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM TDB
3	L3	497507	exchange	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM TDB
4	L4	1755	lattice adj mismatch	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM TDB
5	L5	227518	magnetic and recording	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM TDB

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6	L6	1	1 and 2 and 3 and 4 and 5	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM TDB
7	L7	3	1 and 2 and 4 and 5	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM TDB
8	L8	581	(ru or ruthenium) near alloy	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM TDB
9	L9	84730	lattice	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM TDB
10	L10	11	2 and 5 and 8 and 9	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM TDB

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            14 RU.CO/RC
            58 CO.RU/RC
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=> s ru.cr/rc or cr.ru/rc
            10 RU.CR/RC
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L2          58 RU.CR/RC OR CR.RU/RC

=> s l1 or l2
L3         125 L1 OR L2

=> file ca
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=> s lattice and l3
        258375 LATTICE
           117 L3
L4           7 LATTICE AND L3

=>

=> s match3 and l4
3 IS NOT A RECOGNIZED COMMAND
The previous command name entered was not recognized by the system.
For a list of commands available to you in the current file, enter
"HELP COMMANDS" at an arrow prompt (=>).

=> s matching and l4
         21551 MATCHING
L5           2 MATCHING AND L4
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US006221481B1

(12) **United States Patent**
Wu et al.

(10) **Patent No.: US 6,221,481 B1**
(45) **Date of Patent: Apr. 24, 2001**

(54) **HIGH CR, LOW SATURATION MAGNETIZATION INTERMEDIATE MAGNETIC LAYER FOR HIGH COERCIVITY AND LOW MEDIUM NOISE**

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(73) Assignee: **Seagate Technology LLC**, Scotts Valley, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/188,715**

(22) Filed: **Nov. 10, 1998**

Related U.S. Application Data

(60) Provisional application No. 60/069,538, filed on Dec. 12, 1997.

(51) **Int. Cl.**^{7} **G11B 5/66**

(52) **U.S. Cl.** .... **428/332**; 428/336; 428/694 T; 428/694 TS; 428/900

(58) **Field of Search** .... 428/694 T, 694 TS, 428/900, 336, 332

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"Effects of Cr Intermediate Layers on CoCrPt Thin Film Media on NiA1 Underlayers", Li-Lien Lee, et al., IEEE Transactions on Magnetics, vol. 31, No. 6, Nov. 1995.

"Seed Layer Induced (002) Crystallographic Texture In NiA1 Underlayers", Li-Lien Lee, et al., Journal of Applied Physics 79, No. 8, Apr. 15, 1996.

"The Control And Characterization of The Crystallographic Texture of Longitudinal Thin Film Recording Media", David E. Laughlin, et al., IEEE Transactions on Magnetics vol. 32, No. 5, Sep. 1996.

"The Role of NiA1 Underlayers in Longitudinal Recording Media (Abstract)", C.A. Ross et al., Journal of Applied Physics, vol. 81, No. 8, Apr. 15, 1997.

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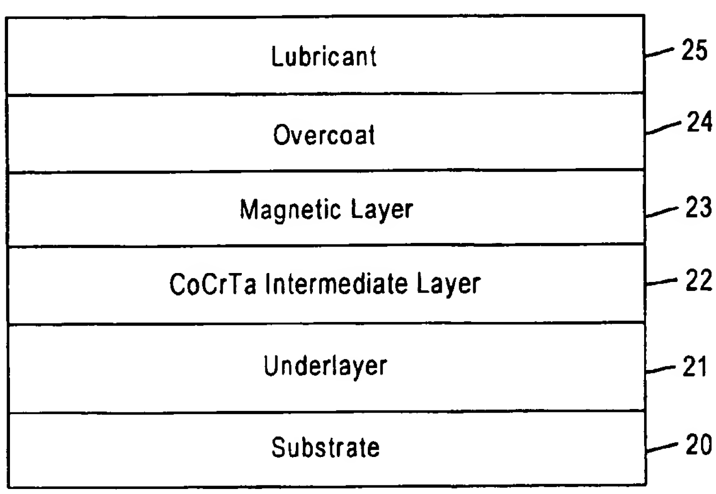
Primary Examiner—Leszek Kiliman
(74) *Attorney, Agent, or Firm*—McDermott, Will & Emery

(57) **ABSTRACT**

High areal density magnetic recording media exhibiting high Hr and low medium noise are formed with a thin CoCrTa intermediate layer having a high Cr content, such as above 15 atomic % to about 20 atomic % Cr, e.g., about 16 to about 17 atomic % Cr. The high Cr content of the CoCrTa intermediate magnetic alloy layer provides a smooth lattice match transition for epitaxial growth of a magnetic layer thereon exhibiting high anisotropy, thereby achieving high Hr and high SNR. Embodiments include depositing the high Cr content CoCrTa intermediate layer at a thickness of about 5 to about 50 Å on a Cr-alloy underlayer.

11 Claims, 4 Drawing Sheets



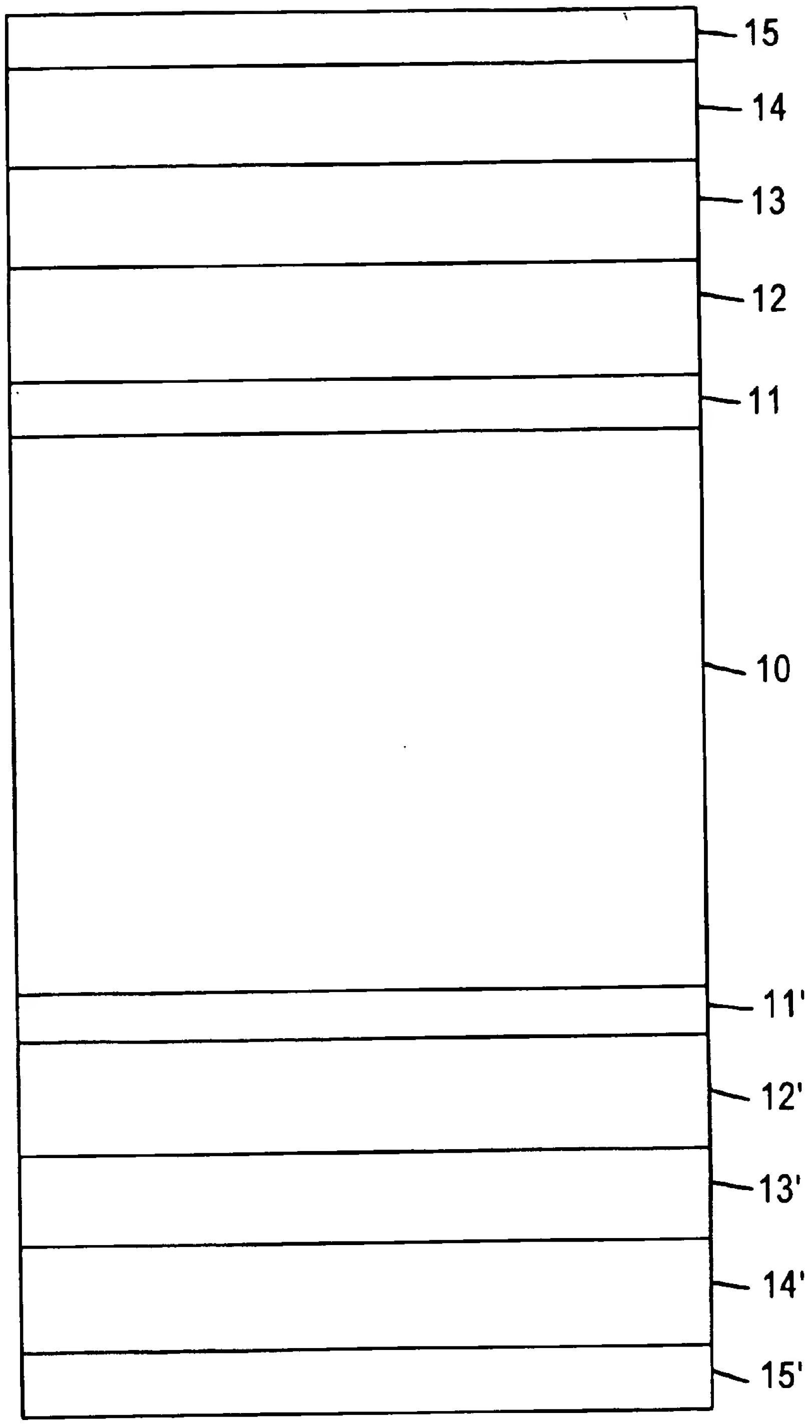


FIG. 1

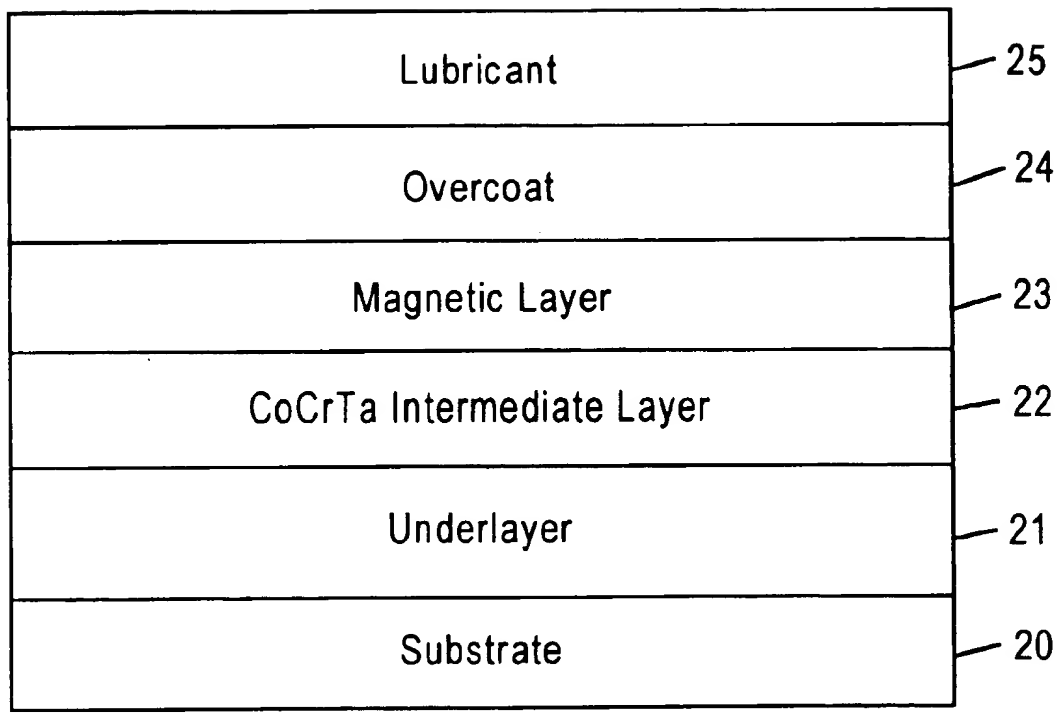

Lubricant
25
Overcoat
24
Magnetic Layer
23
CoCrTa Intermediate Layer
22
Underlayer
21
Substrate
20

FIG. 2

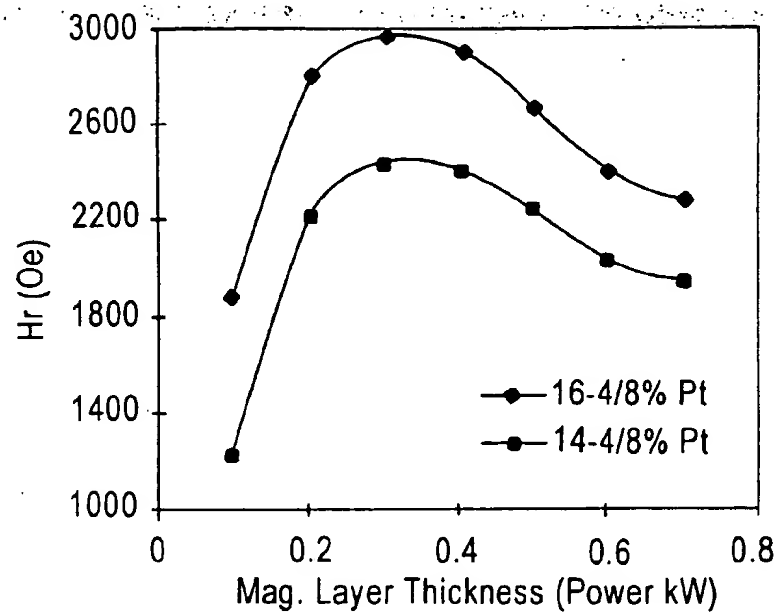

3000
2600
2200
1800
1400
1000
Hr (Oe)
16-4/8% Pt
14-4/8% Pt
0
0.2
0.4
0.6
0.8
Mag. Layer Thickness (Power kW)

FIG. 3A

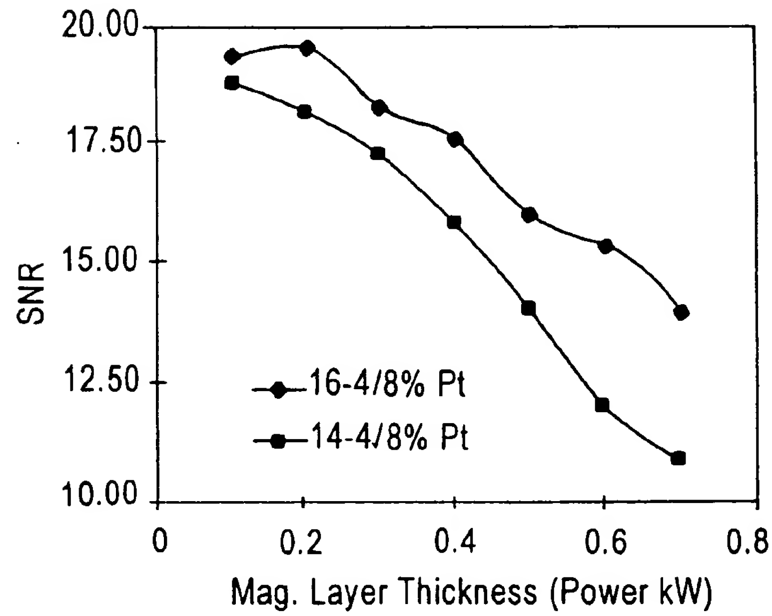

20.00
17.50
15.00
12.50
10.00
SNR
16-4/8% Pt
14-4/8% Pt
0
0.2
0.4
0.6
0.8
Mag. Layer Thickness (Power kW)

FIG. 3B

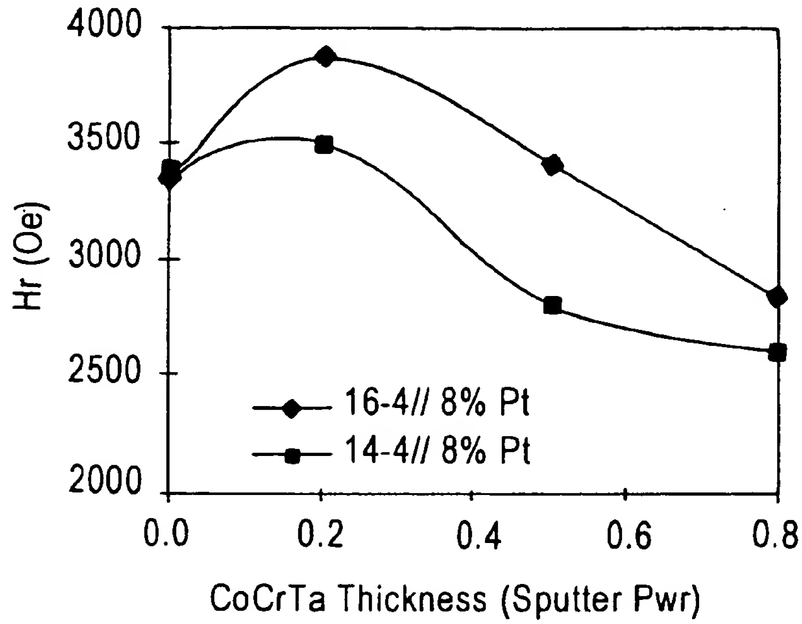

4000
3500
3000
2500
2000
Hr (Oe)
16-4// 8% Pt
14-4// 8% Pt
0.0
0.2
0.4
0.6
0.8
CoCrTa Thickness (Sputter Pwr)

FIG. 4A

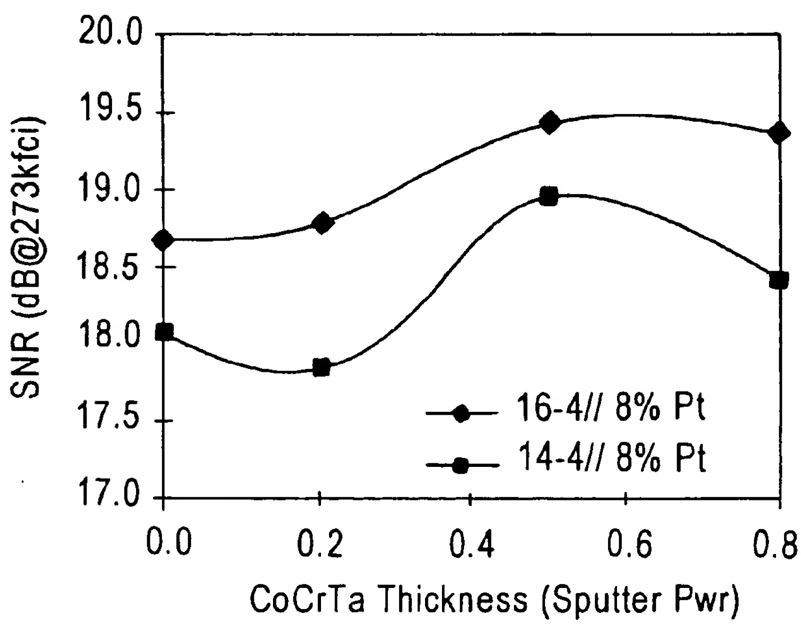

20.0
19.5
19.0
18.5
18.0
17.5
17.0
SNR (dB@273kfci)
16-4// 8% Pt
14-4// 8% Pt
0.0
0.2
0.4
0.6
0.8
CoCrTa Thickness (Sputter Pwr)

FIG. 4B

HIGH CR, LOW SATURATION MAGNETIZATION INTERMEDIATE MAGNETIC LAYER FOR HIGH COERCIVITY AND LOW MEDIUM NOISE

RELATED APPLICATIONS

This application claims priority from Provisional Application Ser. No. 60/069,538 filed on Dec. 12, 1997 entitled "HIGH CONTENT, LOW SATURATION MAGNETIZATION INTERMEDIATE MAGNETIC LAYER FOR HIGH COERCIVITY AND LOW NOISE MEDIA", the entire disclosure of which is hereby incorporated herein by reference.

This application contains subject matter related to subject matter disclosed in copending application Ser. No. 09/188,681, filed on Nov. 10, 1998, now pending and related to subject matter disclosed in copending application Ser. No. 09/188,682, filed on Nov. 10, 1998, now pending the entire disclosures of which are incorporated herein by reference.

1. Technical Field

The present invention relates to magnetic recording media, such as thin film magnetic recording disks, and to a method of manufacturing the media. The invention has particular applicability to high areal density magnetic recording media exhibiting low noise, high remanent coercivity and high coercivity squareness.

2. Background Art

The requirements for increasingly high areal recording density impose increasingly greater demands on thin film magnetic recording media in terms of remanent coercivity (Hr), magnetic remanance (Mr), coercivity squareness (S*), medium noise, i.e., signal-to-noise ratio (SNR), and narrow track recording performance. It is extremely difficult to produce a magnetic recording medium satisfying such demanding requirements.

The linear recording density can be increased by increasing the Hr of the magnetic recording medium and, at the same time, decreasing the medium noise, as by maintaining very fine magnetically non-coupled grains. Medium noise is a dominant factor restricting increased recording density of high density magnetic hard disk drives. Medium noise in thin films is attributed primarily to inhomogeneous grain size and intergranular exchange coupling. Accordingly, in order to increase linear density, medium noise must be minimized by suitable microstructure control.

A conventional longitudinal recording disk medium is depicted in FIG. **1** and comprises a substrate **10**, typically an (Al)-alloy, such as an Al-magnesium (AlMg) alloy plated with a layer of amorphous nickel-phosphorus (NiP). Alternative substrates include glass, ceramic and glass-ceramic materials, as well as graphite. There are typically sequentially sputter deposited on each side of substrate **10** an optional adhesion enhancement layer **11**, **11'**, a seedlayer **12**, **12'**, such as NiP, an underlayer **13**, **13'**, such as chromium (Cr) or a Cr alloy, a magnetic layer **14**, **14'**, such as a cobalt (Co)-based alloy, and a protective overcoat **15**, **15'**, such as a carbon-containing overcoat. Typically, although not shown for illustrative convenience, a lubricant topcoat is applied on the protective overcoat **15**, **15'**.

It is recognized that the magnetic properties, such as Hr, Mr, S* and SNR, which are critical to the performance of a magnetic alloy film, depend primarily upon the microstructure of the magnetic layer which, in turn, is influenced by the underlying layers, such as the underlayer. It is also recognized that underlayers having a fine grain structure are highly desirable, particularly for growing fine grains of hexagonal close packed (HCP) Co alloys deposited thereon.

It has been reported that nickel-aluminum (NiAl) films exhibit a grain size which is smaller than similarly deposited Cr films, which are the underlayer of choice in conventional magnetic recording media. Li-Lien Lee et al., "NiAl Underlayers For CoCrTa Magnetic Thin Films", IEEE Transactions on Magnetics, Vol. 30, No. 6, pp. 3951–3953, 1994. Accordingly, NiAl thin films are potential candidates as underlayers for magnetic recording media for high density longitudinal magnetic recording. However, it was found that the coercivity of a magnetic recording medium comprising a NiAl underlayer is too low for high density recording, e.g. about 2,000 Oersteds (Oe).

Lee et al. subsequently reported that the coercivity of a magnetic recording medium comprising a NiAl underlayer can be significantly enhanced by depositing a plurality of underlayers containing alternative NiAl and Cr layers rather than a single NiAl underlayer. Li-Lien Lee et al., "Effects of Cr Intermediate Layers on CoCrPt Thin Film Media on NiAl Underlayers," Vol. 31, No. 6, Nov. 1995, pp. 2728–2730. It was found, however, that such a magnetic recording medium is characterized by an underlayer structure exhibiting a (110)-dominant crystallographic orientation which does not induce the preferred (1120)-dominant crystallographic orientation in the subsequently deposited Co alloy magnetic layer and is believed to contribute to increased media noise. Li-Lien Lee et al. were able to obtain an underlayer exhibiting a (200)-dominant crystallographic orientation by initially depositing a Cr sub-underlayer directly on the non-magnetic substrate at an undesirably high temperature of about 260° C. using radio frequency (RF) sputtering. However, deposition of a Cr sub-underlayer at such an elevated temperature undesirably results in large grains, which is inconsistent with the reason for employing NiAl as an underlayer. On the other hand, it is very difficult to obtain a Cr (200)-dominant crystallographic orientation, even at elevated temperature such as 260° C., on glass, ceramic and glass ceramic substrates using direct current (DC) magnetron sputtering, which is widely employed in the magnetic recording media industry.

Li-Lien Lee et al. recognized the undesirability of resorting to high deposition temperatures to obtain a (200)-dominant crystallographic orientation in the underlayer structure. It was subsequently reported that an underlayer structure exhibiting a (200)-dominant crystallographic orientation was obtained by depositing a magnesium oxide (MgO) seedlayer using radio frequency (RF) sputtering. Li-Lien Lee et al., "Seed layer induced (**002**) crystallographic texture in NiAl underlayers," J. Appl. Phys. 79 (8), Apr. 15, 1996, pp. 4902–4904; and David E. Laughlin et al., "The Control and Characterization of the Crystallographic Texture of the Longitudinal Thin Film Recording Media," IEEE Transactions on Magnetics, Vol. 32, No. 5, September 1996, pp. 3632–3637. Such a magnetic recording medium, however is not commercially viable from an economic standpoint, because sputtering systems in place throughout the industry making magnetic recording media are based upon direct current (DC) sputtering. Accordingly, RF sputtering an MgO seedlayer is not economically viable. The use of an NiAl underlayer is also disclosed by C. A. Ross et al., "The Role Of An NiAl Underlayers In Longitudinal Thin Film Media" and J. Appl. Phys. 81(a), P.4369, 1996.

Conventional practices in manufacturing magnetic recording media comprise Direct Current (DC) magnetron sputtering and high temperatures in order to obtain Cr segregation in Co-alloy grain boundaries to achieve high Hr

and high SNR. Conventional practices, therefore, employ a high substrate heating temperature, e.g. above about 200° C., e.g. about 230° C. to about 260° C., in order to achieve a desirably high Hr. However, such high substrate heating temperatures result in a reduced S* and, hence, increased medium noise. In order to increase information storage capacity, recording media with higher Hr and lower medium noise are manifestly required. Higher Hr narrows the pulse width, thereby enabling reduction of the bit length for higher recording density, while lower media noise leads to higher SNR.

In order to increase Hr, magnetic alloys containing platinum (Pt), such as Co—Cr—Pt-tantalum (Ta) alloys have been employed. Although Pt enhances film Hr, it was found that Pt also increases media noise. Accordingly, it has become increasingly difficult to achieve high areal recording density while simultaneously achieving high SNR and high Hr.

As media noise predominately stems from exchange and magnetostatic interactions among magnetic grains, SNR can be improved by minimizing such interactions. For example, such interactions can be suppressed by separating or segregating the magnetic grains either physically or chemically. Prior efforts in this area, however, have dealt with relatively low Hr media, e.g. less than about 2,000 Oe. Little effort, to date, has been devoted to increasing Hr and simultaneously reducing media noise for high areal recording density medium.

Accordingly, there exists a need for high density magnetic recording media and methodology for achieving high Hr with high S* and high SNR. There exists a particular need for magnetic recording media containing a CoCrPtTa magnetic alloy layer exhibiting high Hr, high S* and high SNR.

DISCLOSURE OF THE INVENTION

An object of the present invention is a magnetic recording medium for high areal recording density exhibiting low noise, high Hr and high S*.

According to the present invention, the foregoing and other objects are achieved by a magnetic recording medium comprising a non-magnetic substrate; an underlayer on the substrate; an intermediate layer, comprising an alloy of cobalt, greater than about 15 to about 20 atomic % chromium and tantalum, on the underlayer; and a magnetic layer on the intermediate layer.

Another aspect of the present invention is a magnetic recording medium comprising; a non-magnetic substrate; a chromium or chromium alloy underlayer, exhibiting a (200)-dominant crystallographic orientation, on the substrate; an intermediate layer, comprising an alloy of cobalt, about 16 to about 20 atomic % chromium, and about 1 to about 6 atomic % tantalum, exhibiting a (11.0)-dominant crystallographic orientation, on the underlayer; and a CoCrPtTa magnetic alloy layer on the intermediate layer. Additional objects and advantages of the present invention will become readily apparent to those skilled in this art from the following detailed description, wherein only the preferred embodiment of the present invention is shown and described, simply by way of illustration of the best mode contemplated for carrying out the present invention. As will be realized, the present invention is capable of other and different embodiments, and its details are capable of modifications in various obvious respects, all without departing from the present invention. Accordingly, the drawings and description are to be regarded as illustrative in nature, and not as restrictive.

BRIEF DESCRIPTION OF DRAWINGS

FIG. 1 schematically depicts a conventional magnetic recording medium structure.

FIG. 2 schematically depicts a magnetic recording medium in accordance with an embodiment of the present invention.

FIG. 3A shows Hr as a function of magnetic layer thickness for relatively high and relatively low Cr magnetic layers.

FIG. 3B shows SNR as a function of magnetic layer thickness for relatively high and relatively low Cr magnetic alloy layers.

FIG. 4A shows Hr as a function of intermediate layer thickness for relatively high and relatively low Cr intermediate layers.

FIG. 4B shows SNR as a function of intermediate layer thickness for relatively high and relatively low Cr intermediate layers.

DESCRIPTION OF THE INVENTION

The present invention provides magnetic recording media suitable for high areal recording density exhibiting high Hr, high S* and high SNR. In accordance with embodiments of the present invention, desirably high Hr, S* and SNR are achieved by the strategic deposition of a thin magnetic Co-alloy containing Cr and tantalum (Ta). After extensive experimentation and investigation, it was found that the sputter deposition of a CoCrTa alloy having a relatively high Cr content, such as greater than 15 atomic % Cr up to about 20 atomic % Cr, e.g., between about 16 and about 17 atomic % Cr, exhibit low saturation magnetization and a close lattice constant to match underlayer (200) lattice planes, such as a Cr or a Cr alloy underlayer. Accordingly, the high Cr content CoCrTa intermediate alloy layer can be readily grown epitaxially with a (11.0)-dominant crystallographic orientation characteristic of hexagonal close packed (hcp) Co alloys, particularly on a Cr alloy underlayer comprising vanadium (V), titanium (Ti) or molybdenum (Mo). The epitaxially grown high Cr CoCrTa intermediate layer of the present invention with a (11.0)-dominant crystallographic orientation provides a nucleation seedlayer for subsequently deposited highly aniostropic magnetic layers, particular CoCrPtTa layers. Due to what can be characterized as a like-atom growth effect, the high Cr content CoCrTa intermediate layer grows magnetic grains segregated by a non-magnetic Cr or Cr alloy matrix. Such segregation of the magnetic grains provides a superior way to reduce exchange interactions among magnetic grains and suppress medium noise and, simultaneously, reduces the effective saturation magnetization thereby minimizing magnetostatic interaction in the media.

The high Cr content CoCrTa intermediate layer alloys of the present invention typically contain about 1 to about 6 atomic % Ta and can be deposited at a relatively small thickness, e.g. about 5 Å to about 50 Å. The magnetic recording media of the present invention can comprise any of various types of substrates conventionally employed in the manufacture of magnetic recording media, such as NiP-plated Al or Al-alloys, e.g. AlMg, and glass substrates.

It is believed that the matching of the high Cr content CoCrTa intermediate layer with the underlayer, particularly Cr alloy underlayers, enables epitaxial growth of a highly anisotropic magnetic layer, such as CoCrPtTa magnetic layers, having c-axes aligned into the film plane thereby achieving higher Hr and better S*. Thus, magnetic recording

media according to the present invention are highly suitable for longitudinal recording.

The present invention encompasses the use of any of various magnetic alloy layers conventionally employed in the manufacture of magnetic recording media, such as Co alloys, e.g. Co alloys containing Cr, platinum (Pt) and Ta, as well as CoCrTa magnetic layers. In sputter depositing the magnetic layer on the intermediate layer, inclusive of CoCrTa magnetic layers, a defined interface is formed between the intermediate layer and the magnetic layer. The intermediate layer substrate surface provides appropriate crystalline orientation and surface morphology for nucleation and growth of the magnetic layer thereon.

Advantageous results have been achieved employing a CoCrPtTa alloy, with 8%. Pt atomic composition. The present invention also encompasses the use of conventional adhesion layers, such as Cr or Cr-alloys, and seedlayers, such as NiP.

The strategic use of a high Cr content CoCrTa intermediate layer in accordance with embodiments of the present invention also enables sputter deposition of subsequently applied layers at lower substrate temperatures than those conventionally employed, to achieve a desirably high Hr without sacrificing S* or SNR. Thus, sputter deposition of magnetic layers and protective overcoats can be conducted at a temperature less than about 200° C., e.g., about 100° C. to about 150° C.

An embodiment of the present invention is schematically illustrated in FIG. 2 and comprises substrate **20**. For illustrative convenience, the sequentially deposited layers are shown only on one side of substrate **20**. However, it is understood that the present invention comprises sputter depositing sequential layers on both sides of substrate **20**, as in FIG. 1.

Adverting to FIG. **2**, an underlayer **21**, e.g. CrV, is sputter deposited on substrate **20**, which can be NiP-plated AlMg, or a glass, ceramic or glass-ceramic material. A thin high Cr content CoCrTa intermediate layer **22** is sputter deposited on underlayer **21** and a magnetic layer **23**, e.g. CoCrTa or CoCrPtTa, is sputter deposited on intermediate layer **22**. A carbon-containing protective overcoat **24** is sputter deposited on magnetic layer **23**. A lubricant topcoat is then applied to protective overcoat **24**.

EXAMPLE

Magnetic recording media were prepared by direct current (DC) magnetron sputtering on NiP/Al substrates employing a static sputtering system. The base pressure was typically 2×10^{-7} Torr. The substrates were pretreated at 200–300° C. and were biased at −250V. The sputtering argon flow rate was about 15 sccm. The layer configuration comprised a CrV underlayer, $CoCr_{16}Ta_4$ and $CoCr_4Ta_4$ intermediate layers, a $CoCr_{15}Pt_8Ta_4$ magnetic layer and a carbon overcoat. The thickness of the intermediate and magnetic layers were varied. The magnetic properties of the media were tested employing a non-destructive rotating disk magnetometer. The recording characteristics and medium noise were measured at a linear density of 240 kiloflux change per inch (KFCI) employing a Guzik 1601 tester with a magnetoresistive (MR) head with a 0.35 μin gap length and flying at a nominal height of 2.1 μin.

FIG. **3**A shows the Hr as a function of the CoCrPtTa magnetic layer thickness employing CoCrTa intermediate layers containing 16 and 14 atomic % Cr. FIG. **3**B shows the SNR as a function of magnetic layer thickness employing CoCrTa intermediate layers containing 16 and 14 atomic % Cr. It is apparent from FIGS. 3A and 3B that a high Cr content CoCrTa intermediate layer yields higher Hr and SNR. It is believed that the relatively high Cr content in the film segregates the magnetic grains, thereby reducing magnetostatic interactions resulting in higher Hr.

The SNR, as shown in FIG. 3B, is superior for the medium containing the high Cr content CoCrTa intermediate layer. The higher the Cr content, the better the Cr segregation of the magnetic grains and the lower the exchange interactions leading to lower medium noise. Thus, the present invention provides a CoCrTa intermediate alloy having a high Cr content at a reduced thickness, thereby reducing the exchange interactions and improving media performance.

In FIG. 4A, Hr is shown as a function of intermediate alloy layer thickness for media comprising an intermediate layer of Co, 4 Ta and 16 Cr, and Co, 4 Ta, and 14 Cr (atomic %). FIG. 4B shows SNR as a function of intermediate layer thickness for the same media of FIG. 4A. The results reported in FIGS. 4A and 4B again show that as the Cr content of the CoCrTa intermediate layer increases, superior Hr and SNR are achieved.

The present invention, therefore, provides a high areal recording density magnetic recording medium with a strategically engineered CoCrTa intermediate layer having a high Cr content, e.g., about 16% to about 20 atomic % Cr, such as about 15.5 to about 17 atomic % Cr, at a thickness of about 5 to about 30Å. The high Cr content thin CoCrTa intermediate layer provides a smooth lattice match transition for epitaxial growth of subsequently deposited, highly anisotropic CoCrPtTa magnetic layers wherein the c-axes are aligned into the film plane, thereby achieving higher Hr and better S*. The like-atoms-growth effect allows the subsequently deposited CoCrPtTa magnetic alloys to grow in a way that the magnetic grains are well segregated by non-magnetic Cr. The segregation of magnetic grains reduces grain magneto-static interactions, thereby resulting in higher Hr. The segregation of magnetic grains also reduces grain exchange interactions, thereby reducing medium noise.

The present invention provides high areal density magnetic recording medium having a high Hr, high SNR and high S*. The present invention is applicable to the production of various types of magnetic recording media, and is not limited to any particular substrate material, underlayer, magnetic layer, protective overcoat or lubricant topcoat.

Only certain embodiments of the present invention and but a few examples of its versatility are shown and described in the present disclosure. It is to be understood that the present invention is cable of use in various other combinations and environments and is capable of changes and modifications within the scope of the inventive concept as expressed herein.

What is claimed is:

1. A magnetic recording medium comprising:

a non-magnetic substrate;

an underlayer on the substrate;

an intermediate layer, comprising an alloy of cobalt, greater than about 10 to about 20 atomic % chromium and tantalum, on the underlayer; and

a magnetic layer on the intermediate layer; wherein:

the underlayer exhibits a (200)-dominant crystallographic orientation; and

the intermediate layer exhibits a (11.0)-dominant crystallographic orientation.

2. The magnetic recording medium according to claim **1**, wherein the underlayer comprises chromium or a chromium alloy.

3. The magnetic recording medium according to claim 1, wherein the intermediate layer alloy comprises about 1 to about 6 atomic % tantalum.

4. The magnetic recording medium according to claim 3, wherein the underlayer comprises a chromium alloy.

5. The magnetic recording medium according to claim 4, wherein the chromium alloy comprises chromium and vanadium, tantalum or molybdenum.

6. The magnetic recording medium according to claim 3, wherein the magnetic layer comprises an alloy of cobalt, chromium, platinum and tantalum.

7. The magnetic recording medium according to claim 3, wherein the substrate comprises nickel-phosphorous plated on aluminum or an aluminum alloy, or a glass material.

8. The magnetic recording medium according to claim 3, wherein the intermediate layer alloy comprises about 16 to about 20 atomic % chromium.

9. The magnetic recording medium according to claim 8, wherein the intermediate layer alloy comprises about 16 to about 17 atomic % chromium.

10. A magnetic recording medium comprising:

a non-magnetic substrate;

an underlayer on the substrate;

an intermediate layer, comprising an alloy of cobalt, greater than about 10 to about 20 atomic % chromium and tantalum, on the underlayer: and a magnetic layer on the intermediate layer; wherein the intermediate layer has a thickness of about 5 to about 30Å.

11. The magnetic recording medium according to claim 10, wherein the intermediate layer comprises about 1 to about 6 atomic % tantalum.

* * * * *

US006280813B1

(12) United States Patent
Carey et al.

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(54) **MAGNETIC RECORDING MEDIA WITH ANTIFERROMAGNETICALLY COUPLED FERROMAGNETIC FILMS AS THE RECORDING LAYER**

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(52) **U.S. Cl.** .... **428/65.3**; 428/65.5; 428/65.7; 428/694 TM; 428/694 TS

(58) **Field of Search** .... 428/694 EC, 694 TS, 428/694 TP, 694 TM, 65.3, 65.5, 65.7

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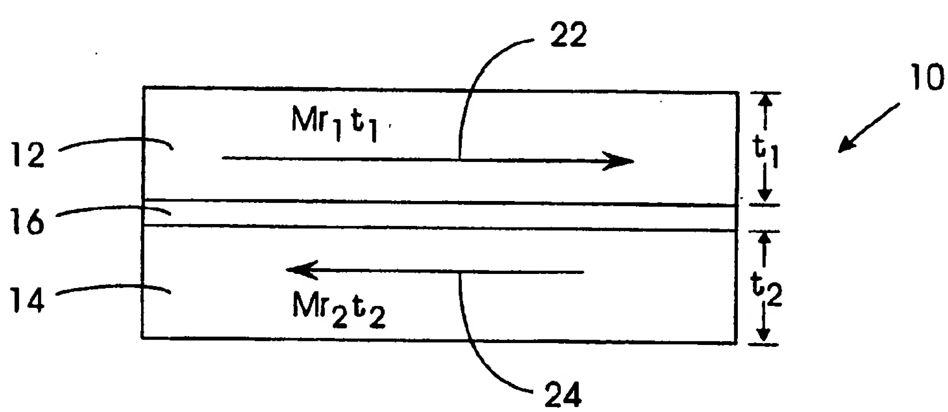
(57) **ABSTRACT**

A magnetic recording medium for data storage uses a magnetic recording layer having at least two ferromagnetic films antiferromagnetically coupled together across a nonferromagnetic spacer film. The magnetic moments of the two antiferromagnetically-coupled films are oriented antiparallel, and thus the net remanent magnetization-thickness product (Mrt) of the recording layer is the difference in the Mrt values of the two ferromagnetic films. This reduction in Mrt is accomplished without a reduction in the thermal stability of the recording medium because the volumes of the grains in the antiferromagnetically-coupled films add constructively. In a magnetic recording rigid disk application, the magnetic layer comprises two ferromagnetic films, each a granular film of a sputter deposited CoPtCrB alloy, separated by a Ru spacer film having a thickness to maximize the antiferromagnetic exchange coupling between the two CoPtCrB films. One of the ferromagnetic films is made thicker than the other, but the thicknesses are chosen so that the net moment in zero applied magnetic field is low, but nonzero.

18 Claims, 3 Drawing Sheets



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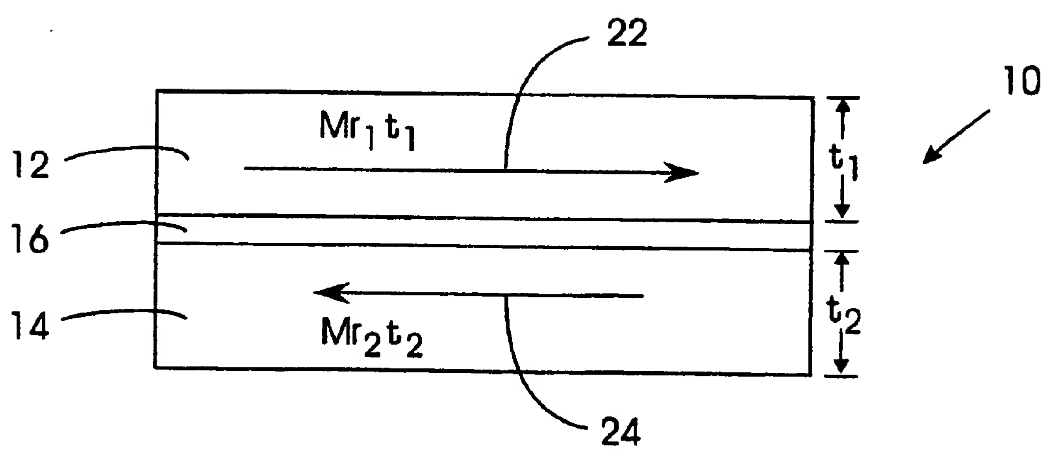

FIG. 1

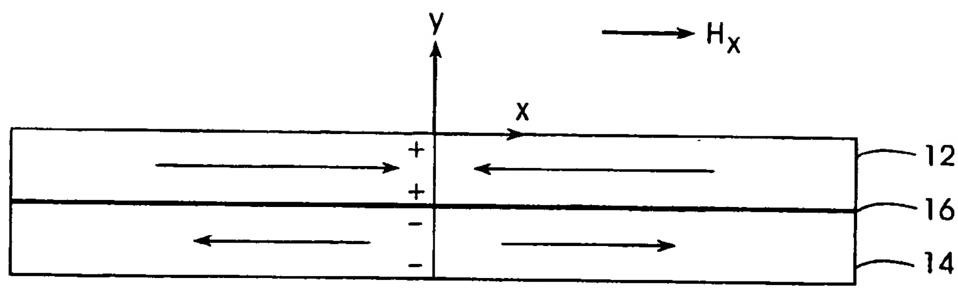
y
H_x
x
+
+
-
-
12
16
14

FIG. 2A

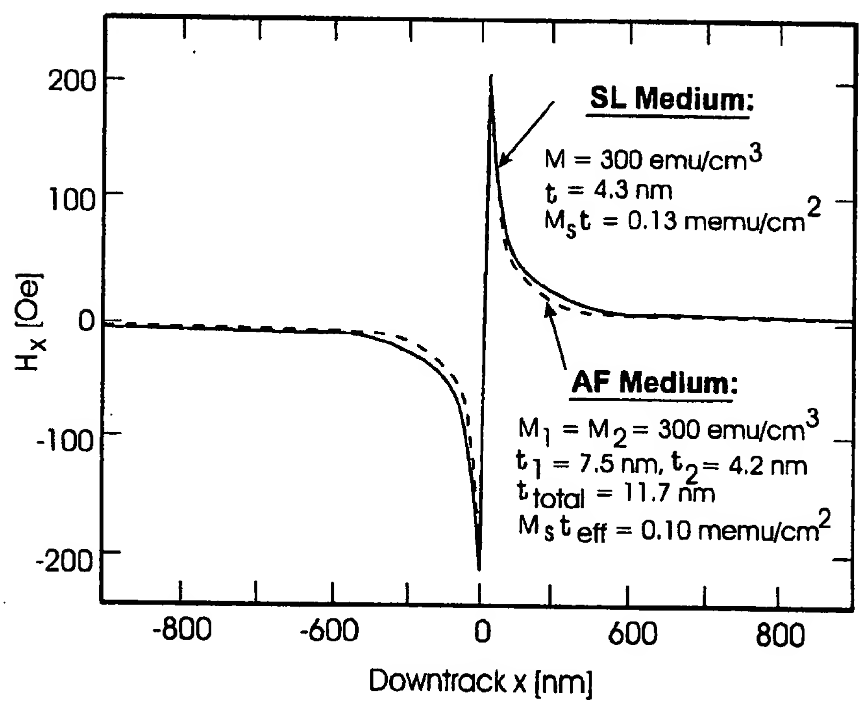
SL Medium:
M = 300 emu/cm^3
t = 4.3 nm
$M_s t$ = 0.13 memu/cm^2
AF Medium:
$M_1 = M_2$ = 300 emu/cm^3
t_1 = 7.5 nm, t_2 = 4.2 nm
t_{total} = 11.7 nm
$M_s t_{eff}$ = 0.10 memu/cm^2
200
100
0
-100
-200
H_x [Oe]
-800
-600
0
600
800
Downtrack x [nm]

FIG. 2B

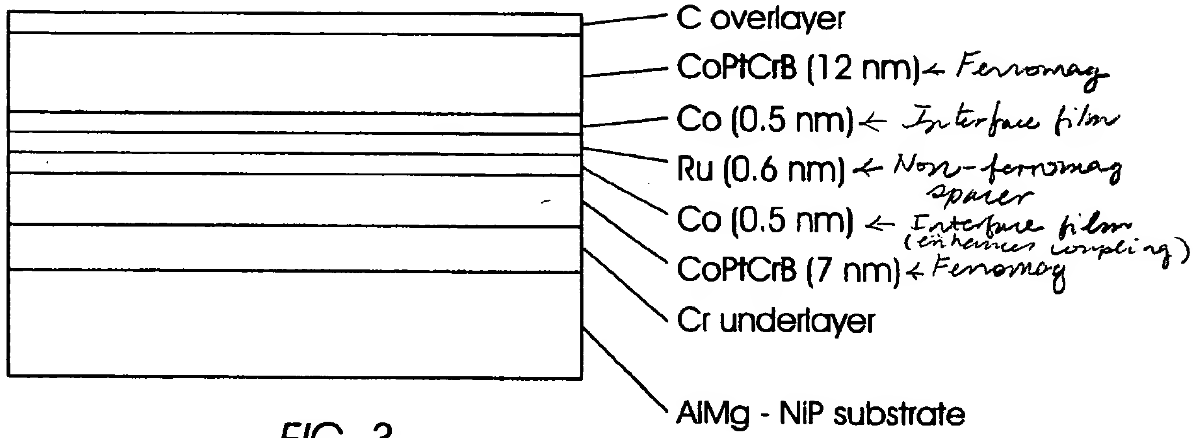
C overlayer
CoPtCrB (12 nm) ← Ferromag
Co (0.5 nm) ← Interface film
Ru (0.6 nm) ← Non-ferromag spacer
Co (0.5 nm) ← Interface film (enhances coupling)
CoPtCrB (7 nm) ← Ferromag
Cr underlayer
AlMg - NiP substrate

FIG. 3

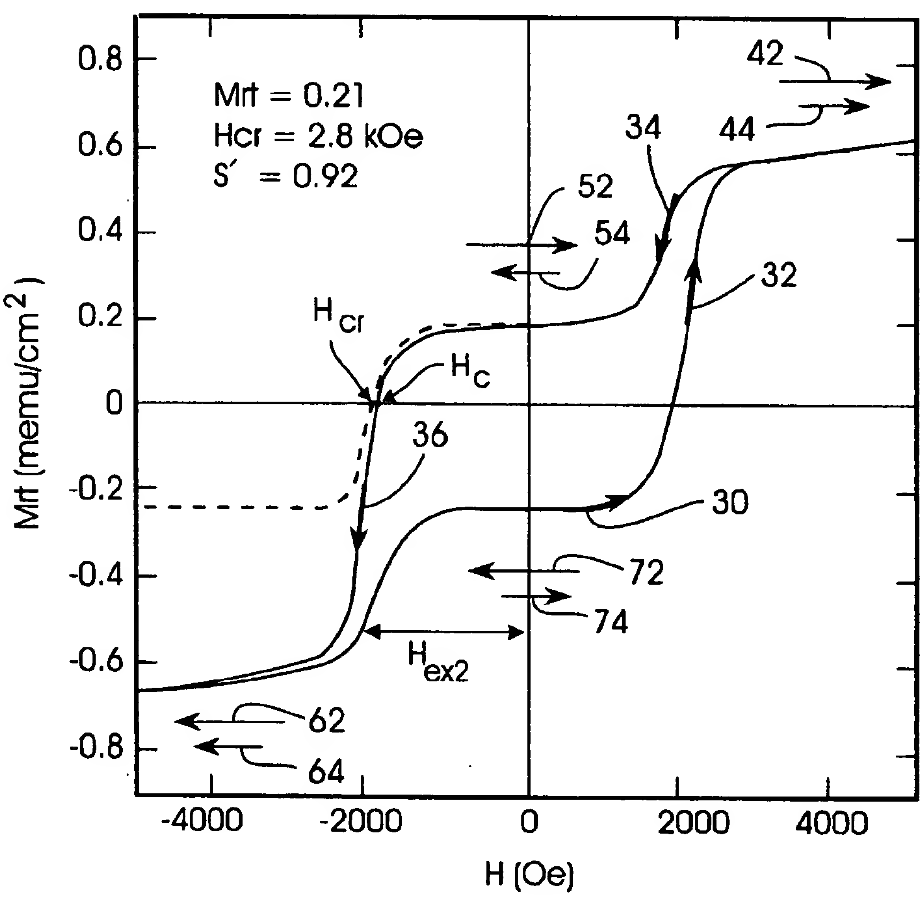
Mrt = 0.21
Hcr = 2.8 kOe
S′ = 0.92
Mrt (memu/cm²)
H (Oe)
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-4000
-2000
0
2000
4000
42
44
34
52
54
32
H cr
H c
36
30
72
74
H ex2
62
64

FIG. 4

MAGNETIC RECORDING MEDIA WITH ANTIFERROMAGNETICALLY COUPLED FERROMAGNETIC FILMS AS THE RECORDING LAYER

TECHNICAL FIELD

This invention relates generally to magnetic recording media, and more particularly to thermally stable high density media.

BACKGROUND OF THE INVENTION

Conventional magnetic recording media, such as the magnetic recording disks in hard disk drives, typically use a granular ferromagnetic layer, such as a sputter-deposited cobalt-platinum (CoPt) alloy, as the recording medium. Each magnetized domain in the magnetic layer is comprised of many small magnetic grains. The transitions between magnetized domains represent the "bits" of the recorded data. IBM's U.S. Pat. Nos. 4,789,598 and 5,523,173 describe this type of conventional rigid disk.

As the storage density of magnetic recording disks has increased, the product of the remanent magnetization Mr (the magnetic moment per unit volume of ferromagnetic material) and the magnetic layer thickness t has decreased. Similarly, the coercive field or coercivity (H_c) of the magnetic layer has increased. This has led to a decrease in the ratio Mrt/H_c. To achieve the reduction in Mrt, the thickness t of the magnetic layer can be reduced, but only to a limit because the layer will exhibit increasing magnetic decay, which has been attributed to thermal activation of small magnetic grains (the superparamagnetic effect). The thermal stability of a magnetic grain is to a large extent determined by K_uV, where K_u is the magnetic anisotropy constant of the layer and V is the volume of the magnetic grain. As the layer thickness is decreased, V decreases. If the layer thickness is too thin, the stored magnetic information will no longer be stable at normal disk drive operating conditions.

One approach to the solution of this problem is to move to a higher anisotropy material (higher K_u). However, the increase in K_u is limited by the point where the coercivity H_c, which is approximately equal to K_u/Mr, becomes too great to be written by a conventional recording head. A similar approach is to reduce the Mr of the magnetic layer for a fixed layer thickness, but this is also limited by the coercivity that can be written. Another solution is to increase the intergranular exchange, so that the effective magnetic volume V of the magnetic grains is increased. However, this approach has been shown to be deleterious to the intrinsic signal-to-noise ratio (SNR) of the magnetic layer.

It is known that substantially improved SNR can be achieved by the use of a laminated magnetic layer of two (or more) separate magnetic layers that are spaced apart by an nonmagnetic spacer layer. This discovery was made by S. E. Lambert, et al., "Reduction of Media Noise in Thin Film Metal Media by Lamination", *IEEE Transactions on Magnetics*, Vol. 26, No. 5, September 1990, pp. 2706–2709, and subsequently patented in IBM's U.S. Pat. No. 5,051,288. The reduction in intrinsic media noise by lamination is believed due to a decoupling of the magnetic interaction or exchange coupling between the magnetic layers in the laminate. The use of lamination for noise reduction has been extensively studied to find the favorable spacer layer materials, including Cr, CrV, Mo and Ru, and spacer thicknesses, from 5 to 400 Å, that result in the best decoupling of the magnetic layers, and thus the lowest media noise. This work has been reported in papers by E. S. Murdock, et al., "Noise Properties of Multilayered Co-Alloy Magnetic Recording Media", *IEEE Transactions on Magnetics*, Vol. 26, No. 5, September 1990, pp. 2700–2705; A. Murayama, et al., "Interlayer Exchange Coupling in Co/Cr/Co Double-Layered Recording Films Studied by Spin-Wave Brillouin Scattering", *IEEE Transactions on Magnetics*, Vol. 27, No. 6, November 1991, pp. 5064–5066; and S. E. Lambert, et al., "Laminated Media Noise for High Density Recording", *IEEE Transactions on Magnetics*, Vol. 29, No.1, January 1993, pp. 223–229. U.S. Pat. No. 5,462,796 and the related paper by E. Teng et al., "Flash Chromium Interlayer for High Performance Disks with Superior Noise and Coercivity Squareness", *IEEE Transactions on Magnetics*, Vol. 29, No. 6, November 1993, pp. 3679–3681, describe a laminated low-noise disk that uses a discontinuous Cr film that is thick enough to reduce the exchange coupling between the two magnetic layers in the laminate but is so thin that the two magnetic layers are not physically separated.

What is needed is magnetic recording media that will support very high density recording while retaining good thermal stability and SNR.

SUMMARY OF THE INVENTION

The invention is a magnetic recording medium wherein the magnetic recording layer is at least two ferromagnetic films antiferromagnetically coupled together across a nonferromagnetic spacer film. Because the magnetic moments of the two antiferromagnetically-coupled films are oriented antiparallel, the net remanent magnetization-thickness product (Mrt) of the recording layer is the difference in the Mrt values of the two ferromagnetic films. This reduction in Mrt is accomplished without a reduction in the thermal stability of the recording medium because the volumes of the grains in the antiferromagnetically-coupled films add constructively. The medium also enables much sharper magnetic transitions to be achieved with reduced demagnetization fields, resulting in a higher linear bit density for the medium. In one embodiment the magnetic recording medium comprises two ferromagnetic films, each a granular film of a sputter deposited CoPtCrB alloy, separated by a Ru spacer film having a thickness to maximize the antiferromagnetic exchange coupling between the two CoPtCrB films. One of the ferromagnetic films is made thicker than the other, but the thicknesses are chosen so that the net moment in zero applied magnetic field is low, but nonzero.

For a fuller understanding of the nature and advantages of the present invention, reference should be made to the following detailed description taken together with the accompanying figures.

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 is a schematic sectional view of the antiferromagnetically (AF) coupled magnetic recording layer in a recording medium according to the present invention.

FIG. 2A is a schematic illustration of the AF-coupled layer illustrating the orientations of the moments of the ferromagnetic films at a recorded magnetic transition.

FIG. 2B is a graph of calculated magnetic field above the AF-coupled layer and a single layer (SL) medium as a function of downtrack position from a transition.

FIG. 3 is a schematic sectional view of the disk structure of the present invention illustrating the substrate, underlayer, the films in the AF-coupled layer, and the protective overcoat.

FIG. 4 is a magnetic hysteresis loop for the structure with the AF-coupled layer of FIG. 3.

DETAILED DESCRIPTION OF THE INVENTION

The magnetic recording medium of the present invention has a recording layer formed of two or more ferromagnetic films that are exchange-coupled antiferromagnetically (AF) to their neighboring ferromagnetic films by one or more nonferromagnetic spacer films. This is shown schematically in FIG. **1** for a recording layer **10** made up of two ferromagnetic films **12**, **14** separated by a nonferromagnetic spacer film **16**. The nonferromagnetic spacer film **16** thickness and composition are chosen so that the magnetic moments **22**, **24** of adjacent films **12**, **14**, respectively, are AF-coupled through the nonferromagnetic spacer film **16** and are antiparallel in zero applied fields.

The AF coupling of ferromagnetic films via a nonferromagnetic transition metal spacer film has been extensively studied and described in the literature. In general, the exchange coupling oscillates from ferromagnetic to antiferromagnetic with increasing spacer film thickness. This oscillatory coupling relationship for selected material combinations is described by Parkin et al. in "Oscillations in Exchange Coupling and Magnetoresistance in Metallic Superlattice Structures: Co/Ru, Co/Cr and Fe/Cr", *Phys. Rev. Lett.*, Vol. 64, p. 2034 (1990). The material combinations include ferromagnetic films made of Co, Fe, Ni, and their alloys, such as Ni-Fe, Ni-Co, and Fe-Co, and nonferromagnetic spacer films such as ruthenium (Ru), chromium (Cr), rhodium (Rh), iridium (Ir), copper (Cu), and their alloys. For each such material combination, the oscillatory exchange coupling relationship has to be determined, if not already known, so that the thickness of the nonferromagnetic spacer film is selected to assure antiferromagnetic coupling between the two ferromagnetic films. The period of oscillation depends on the nonferromagnetic spacer material, but the strength and phase of the oscillatory coupling also depends on the ferromagnetic material and interfacial quality. The oscillatory antiferromagnetic coupling of ferromagnetic films has been used in spin-valve type giant magnetoresistance (GMR) recording heads to design continuous magnetized antiferromagnetically coupled films whose magnetic moments are rigidly coupled together antiparallel during operation of the head. These type of spin-valve structures are described, for example, in IBM patents 5,408,377 and 5,465,185. The '185 patent describes a structure used in many commercially available spin-valve GMR heads, namely a laminated antiparallel pinned ferromagnetic layer having ferromagnetic films whose moments are rigidly coupled together and remain stationary during operation of the head.

The films **12**, **14** have magnetic moment values of Mr_1t_1 and Mr_2t_2, respectively. (Because the remanent magnetization Mr is expressed as the magnetic moment per unit volume of ferromagnetic material, the product Mrt is the magnetic moment per unit area for a magnetic layer of thickness t.) For this AF-coupled structure the orientations of the magnetic moments **22**, **24** of adjacent films **12**, **14**, respectively, are aligned antiparallel and thus add destructively to reduce the magnetic moment of the composite layer **10**. The arrows **22**, **24** represent the moment orientations of individual magnetic domains that are directly above and below one another across the AF coupling film **16**. In the absence of an applied magnetic field, when the ferromagnetic film **14** is deposited onto the medium substrate, it will have a granular structure with multiple adjacent grains being coupled together to form individual magnetic domains. In the absence of an applied magnetic field the moments of these domains in film **14** will be essentially randomly oriented. The spacer film or AF-coupling film **16** is then deposited to the correct thickness directly on ferromagnetic film **14**. Next, the second ferromagnetic film **12** is deposited directly on the AF coupling film **16**. As the grains of ferromagnetic film **12** grow they will form magnetic domains with moment orientations that are antiparallel to the moment orientations of ferromagnetic film **14** that are directly across the AF coupling film **16**.

The type of ferromagnetic material and the thickness values t_1, t_2 of the ferromagnetic films **12**, **14** are chosen so that the net moment in zero applied field will be low, but nonzero. For the case shown in FIG. 1, the Mrt for the structure is given by $Mr_1t_1-Mr_2t_2$. In the preferred embodiment, Mr_1t_1 should be $>Mr_2t_2$. This may be accomplished by using the same ferromagnetic materials in the two films **12**, **14** and having t_1 be greater than t_2, or the magnetization (the magnetic moment per unit volume of material) of the two ferromagnetic films may be made different by using different ferromagnetic materials for the two films. While FIG. 1 is shown for a two-film structure with a single spacer film **16**, the invention is extendible to structures with multiple spacer films and multiple ferromagnetic films.

The present invention has a number of advantages over a magnetic layer formed as a single layer of ferromagnetic material. Low remanent magnetization can be obtained without using ultra-thin magnetic layers or low-magnetization alloys. This avoids the problems of thermal instability and difficulty in writing discussed above. If the magnetic layer in FIG. **1** is compared to a single-layer consisting of only film **12**, for example, the addition of the AF-coupled ferromagnetic film **14** reduces the net magnetic moment of the composite structure without decreasing either the thickness or the magnetization of film **12**.

The enhanced thermal stability of the composite structure compared to a single magnetic layer arises because the anisotropy of the grains in both films **12** and **14** are substantially uniaxial, and thus can add constructively even if the magnetic moments of films **12**, **14** are antiparallel. The resulting stability parameter of the coupled system K_uV is given by $Ku_1V_1<KuV<(Ku_1V_1+Ku_2V_2)$, where Ku_1V_1 and Ku_2V_2 are the anisotropy energies of typical grains in films **12**, **14**, respectively. The upper limit for the composite stability parameter $KuV=Ku_1V_1+Ku_2V_2$ will be achieved for the case when magnetic grains in film **12** and **14** are strongly coupled and share a common anisotropy axis direction. The magnetic volume V of the composite structure (layer **10**) that determines the thermal stability will be approximately the sum of the volumes of the exchange-coupled grains in films **12** and **14**, whereas the magnetic moment of layer **10** is the difference of the individual moments of films **12**, **14**. The antiferromagnetic coupling between the two ferromagnetic films provides a mechanism to increase the effective film thickness while reducing the net Mrt value of the composite structure. Thus the ferromagnetic films can contain very small diameter grains and maintain thermal stability.

The AF-coupled medium according to the present invention is shown schematically in FIG. 2A with a recorded or written magnetic transition. The plus (+) and minus (−) symbols represent the magnetic poles arising from the transition. The calculated longitudinal field (H_x) 10 nm above the surface of the AF-coupled medium is shown in FIG. 2B as a function of X direction or downtrack position

from the transition. The moment and thickness values for the two films **12**, **14** and the calculated Mrt for the AF-coupled layer are listed in FIG. **2B**. For comparison, FIG. **2B** also shows model calculations of longitudinal magnetic field arising from transitions in a single-layer (SL) medium that has a similar Mrt. The thickness values (t_1 and t_2) were chosen such that the peak longitudinal field was the same for the AF-coupled medium compared to the SL medium. The total thickness of the ferromagnetic material in the AF-coupled medium is 2.7 times thicker. Therefore, the AF-coupled medium should be more thermally stable than the SL medium. The longitudinal field profile in the down-track direction decays faster for the AF-coupled medium, resulting in a sharper transition. This indicates that the transitions can be spaced closer than in the SL medium, resulting in a higher linear bit density for the medium. While not shown in FIG. 2B, calculations have also shown that the demagnetization field from a transition within the AF-coupled medium also decreases faster than in the SL medium. In addition, the magnitude and sign of the demagnetization field depends on the Y position (see FIG. 2A) within the medium. Thus for certain Y positions within the medium, the demagnetization field is reduced to zero. Small demagnetization fields are desired because they can affect other transitions and cause the transition to demagnetize itself.

The present invention has been demonstrated using conventional CoPtCrB longitudinal recording media alloys for the ferromagnetic films. An example structure is shown in FIG. 3. The structure was fabricated using conventional sputter deposition equipment and processes. The films forming the structure were grown onto a Cr underlayer deposited onto a substrate of a AlMg disk blank with a nickel-phosphorus (NiP) surface coating, with the substrate temperature at approximately 200° C. The ferromagnetic films are CoPtCrB, with the top film corresponding to film **12** in FIG. **1** being thicker than the bottom ferromagnetic film corresponding to film **14** in FIG. **1** (12 nm vs. 7 nm). The nonferromagnetic spacer film is a 0.6 nm Ru film. As with single-layer media, it is advantageous to use a granular ferromagnetic material with isolated magnetic grains to lower the media noise. The Ru film thickness was chosen to be at the first antiferromagnetic peak in the oscillatory coupling relationship. For this example, each CoPtCrB ferromagnetic film included an interface film consisting essentially of 0.5 nm of Co at the interface with the Ru film. These ultra-thin Co films increase the interfacial moment between the ferromagnetic films and the Ru film, resulting in enhanced antiferromagnetic coupling. However, antiferromagnetic exchange coupling has been demonstrated without incorporating the Co interface films in the CoPtCrB ferromagnetic films.

FIG. **4** shows the major hysteresis loop (solid line) and the remanent hysteresis loop (dashed line) measured at T=350° K. for the structure of FIG. **3**. Referring first to the remanent hysteresis loop, it is obtained by saturating the AF-coupled layer in a positive field and then applying an increasing reverse negative field and measuring the remanent moment in the layer after the negative field is applied. The remanent loop is a plot of the remanent moment versus the magnitude of the reverse field. For this sample the remanent loop shows Mrt=0.21, the remanent coercive field H_{cr}=3.2 kOe, and S'=0.92 at room temperature, where S' is a measure of the slope of the remanent loop at H_{cr}. For comparison, a similarly grown 15-nm single layer of the same CoPtCrB alloy has properties of Mrt=0.38, H_{cr}=2.4 kOe and S'=0.76 at room temperature. Thus, the AF-coupled medium allows a significantly lower Mrt to be achieved with a greater total magnetic layer thickness.

Referring next to the major hysteresis loop of FIG. **4**, the pairs of horizontal arrows indicate the orientation of the ferromagnetic films in the AF-coupled layer at different points in the hysteresis loop. The applied field is increased in the positive direction (arrows **30**, **32**). For large applied fields (>3000 Oe), the antiferromagnetic coupling is overcome and the moments of the two ferromagnetic films are both parallel to the applied field (arrows **42**, **44**). As the applied field is reduced (arrow **34**) the moment of the thinner bottom ferromagnetic film reverses and becomes antiparallel to the moment of the thicker top ferromagnetic film (arrows **52**, **54**) and to the applied field with a drop in the net moment. This switch occurs roughly at the exchange field felt by the bottom film (H_{ex2}=2000 Oe) arising from the coupling across the Ru film. The value of $H_{ex2}=J_{ex}/M_2t_2$, where J_{ex} is the antiferromagnetic interface exchange energy density across the Ru spacer layer and M_2 and t_2 are the magnetization and thickness of the bottom ferromagnetic film, respectively. For an antiparallel alignment of the ferromagnetic films to be realized requires that H_{ex2} exceed the coercive field required to reverse the bottom ferromagnetic film (H_{c2}). H_{c2} is the coercive field of the bottom film, assuming no exchange interaction with the top ferromagnetic film. Thus, the magnetic properties and thickness of the bottom film, as well as the AF-coupling film, must be designed to maintain $H_{ex2}>H_{c2}$.

The remanent state after saturation in a positive field is given by the moment of the top ferromagnetic film parallel to the field direction and the moment of the bottom ferromagnetic film antiparallel to the positive field direction (arrows **52**, **54**). In a reverse applied field (arrow **36**), the magnetic state is stable until the moment of the top ferromagnetic film reverses and the moments of both films are parallel and aligned in the negative saturation state (arrows **62**, **64**). The switching of the moment of the top ferromagnetic film determines the coercive field of the AF-coupled layer and is given by $H_c=H_{ex1}+H_{c1}$ where H_{ex1} is the exchange field acting on the top ferromagnetic film ($H_{ex1}=J_{ex}/M_1t_1$) and H_{c1} is the coercive field of the top ferromagnetic film, assuming no interaction with the bottom ferromagnetic film. Thus, the properties of the top ferromagnetic film and the AF-coupling film must be designed to maintain H_c of the composite structure below the expected write field of the head. For this example the pathway to go from one remanent state (arrows **52**, **54**) to the next remanent state (arrows **72**, **74**) goes through an intermediate state where the moments of the two films are parallel (arrows **62**, **64**). Thus, in contrast to AF-coupled structures used in spin-valve GMR recording heads, the moments of the ferromagnetic films in the medium according to the present invention are not rigidly coupled together across the AF-coupling film because the coupling must be overcome to write on the medium. The hysteresis loop of FIG. **4** exhibits the desired feature of an AF-coupled layer, i.e., a low remanent magnetization relative to the saturation magnetization.

Recording performance tests on the AF-coupled layer were performed using a conventional longitudinal recording head. Signal to noise ratio measurements determined a media S_oNR of 31.9 dB at 9500 flux changes per millimeter (fc/mm), where S_o is the isolated pulse amplitude and N is the integrated media noise at 9500 fc/mm recording density. These results demonstrate the viability of AF-coupled magnetic layers for data storage.

The AF-coupled media according to the present invention has also been demonstrated for structures with and without

one or both Co interface films, with and without one or both CoCr interface layers, and with CoCrPtTa ferromagnetic films.

While the present invention has been particularly shown and described with reference to the preferred embodiments, it will be understood by those skilled in the art that various changes in form and detail may be made without departing from the spirit scope, and teaching of the invention. Accordingly, the disclosed invention is to be considered merely as illustrative and limited in scope only as specified in the appended claims.

What is claimed is:

1. A magnetic recording medium comprising:

a substrate;

a magnetic recording layer on the substrate and comprising a first ferromagnetic film having a magnetic moment per unit area, a nonferromagnetic spacer film on the first ferromagnetic film, and a second ferromagnetic film having a magnetic moment per unit area different from the moment per unit area of the first ferromagnetic film and being formed on the spacer film, the second ferromagnetic film being exchange coupled antiferromagnetically to the first ferromagnetic film across the spacer film, the magnetic recording layer exhibiting a major hysteresis loop with two remanent magnetic states in the absence of an applied magnetic field; and

wherein the orientations of the moments of the first and second ferromagnetic films are substantially antiparallel in each remanent state, but the first ferromagnetic film's moment orientation in one remanent state is substantially antiparallel to its orientation in the other remanent state.

2. The medium of claim 1 further comprising a second nonferromagnetic spacer film on the second ferromagnetic film and a third ferromagnetic film on the second spacer film, the third ferromagnetic film being exchange coupled antiferromagnetically to the second ferromagnetic film across the second spacer film.

3. The medium of claim 1 wherein the first ferromagnetic film has a thickness t1 and a magnetization M1, the second ferromagnetic film has a thickness t2 and a magnetization M2, and wherein the magnetic moments per unit area (M1xt1) and (M2xt2) of the first and second ferromagnetic films, respectively, are different from one another.

4. The medium of claim 3 wherein the first and second ferromagnetic films are formed of the same material, and wherein t1 is different from t2.

5. The medium of claim 3 wherein the first and second ferromagnetic films are formed of different materials and wherein t1 and t2 are substantially the same thickness.

6. The medium of claim 1 wherein the spacer film is formed of a material selected from the group consisting of ruthenium (Ru), chromium (Cr), rhodium (Rh), iridium (Ir), copper (Cu), and their alloys.

7. The medium of claim 1 wherein the first and second ferromagnetic films are made of a material selected from the group consisting of Co, Fe, Ni, and their alloys.

8. The medium of claim 1 wherein the first ferromagnetic film includes an interface film consisting essentially of cobalt located at the interface of the first ferromagnetic film and the spacer film.

9. The medium of claim 1 wherein the second ferromagnetic film includes an interface film consisting essentially of cobalt located at the interface of the second ferromagnetic film and the spacer film.

10. The medium of claim 1 further comprising an underlayer located on the substrate between the substrate and the magnetic recording layer.

11. The medium of claim 1 further comprising a protective overcoat formed over the magnetic recording layer.

12. A magnetic recording disk comprising:

a substrate;

an underlayer on the substrate;

a magnetic recording layer on the underlayer and comprising a first cobalt alloy ferromagnetic film having magnetic moment per unit area and comprising multiple magnetic domains with the orientations of the moments of the domains being generally randomly oriented, a nonferromagnetic spacer film of a material selected from the group consisting of ruthenium (Ru), chromium (Cr), rhodium (Rh), iridium (Ir), copper (Cu), and their alloys formed on and in contact with the first ferromagnetic film, and a second cobalt alloy ferromagnetic film having magnetic moment per unit area different then the magnetic moment per unit area of the first ferromagnetic film and comprising multiple magnetic domains formed on and in contact with the spacer film, the spacer film having a thickness sufficient to induce domains of the second ferromagnetic film to be exchange coupled antiferromagnetically to associated domains of the first ferromagnetic film across the spacer film with the orientations of the moments of the domains in the second ferromagnetic film being substantially antiparallel to the orientations of the moments of their associated domains in the first ferromagnetic film; and

a protective overcoat formed on the magnetic recording layer.

13. The disk of claim 12 further comprising a second nonferromagnetic spacer film formed on and in contact with the second ferromagnetic film and a third ferromagnetic film formed on and in contact with the second spacer film, the thickness of the second spacer film being sufficient to induce the third ferromagnetic film to be exchange coupled antiferromagnetically to the second ferromagnetic film across the second spacer film.

14. The disk of claim 12 wherein the first ferromagnetic film has a thickness t1 and a magnetization M1, the second ferromagnetic film has a thickness t2 and a magnetization M2, and wherein the magnetic moment per unit area (M1×t1) and (M2xt2) of the first and second ferromagnetic films, respectively, are different from one another.

15. The disk of claim 14 wherein the first and second ferromagnetic films are formed of the same material, and wherein t1 is different from t2.

16. The disk of claim 14 wherein the first and second ferromagnetic films are formed of different materials and wherein t1 and t2 are substantially the same thickness.

17. The disk of claim 14 wherein the first ferromagnetic film includes an interface film consisting essentially of cobalt located at the interface of the first ferromagnetic film and the spacer film.

18. The disk of claim 14 wherein the second ferromagnetic film includes an interface film consisting essentially of cobalt located at the interface of the second ferromagnetic film and the spacer film.

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